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14. ABSTRACT
We summarize the results of our most recent ONR Contract, "Reduced Rank Wiener Filters in Optimized Coordinates for Partially Adaptive Filtering in Passive and Active Sonar Arrays," ONR Contract N00014-01-1-1019, by giving a narrative account of what we have found for reduced-rank detection and estimation, conjugate direction Wiener filters, beamforming and diversity combining, and matched and adaptive subspace detection. We offer a discussion of open questions, as these inform our continuing work, under ONR support.

The work reported here falls into the category of fundamental research addressed to passive sonar surveillance from large sonar arrays deployed in complex acoustic environments.

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Reduced Rank Wiener Filters in Optimized Coordinates for Partially Adaptive Filtering in Passive and Active Sonar Arrays, ONR Contract N00014-01-1-1019: Final Report

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1 Introduction

We summarize the results of our most recent ONR contract, "Reduced Rank Wiener Filters in Optimized Coordinates for Partially Adaptive Filtering in Passive and Active Sonar Arrays," ONR Contract N00014-01-1-1019, by giving a narrative account of what we have found and where we have published it. We offer a discussion of open questions, as these inform our continuing work, under ONR support.

Our work falls into the category of *fundamental research initiatives* addressed to *passive sonar surveillance* from *large sonar arrays* deployed in *complex acoustic environments.*

2 Coordinate Systems for Reduced Rank Detection and Estimation, including Conjugate Direction and Multistage Wiener Filters

2.1 Narrative

One of the main goals of our research program was to derive structures and algorithms for *filtering in optimized coordinates of low-dimensional subspaces*, with a view to reducing computational complexity and improving convergence time of adaptive algorithms.

Our recent ASAP 2003 paper, ref [1] below, brings a lot of insight into the multistage Wiener filter (MSWF). It establishes that for every MSWF, whether or not it is orthogonal, there is a corresponding conjugate *direction* Wiener filter (CDWF). This means the entire literature of conjugate direction algorithms, including quasi-Newtons, is opened up for exploration of algorithms. These algorithms can generate coordinate systems for low-dimensional subspaces other than the Krylov subspace, which is what we are stuck with in *orthogonal* MSWFs and conjugate *gradient* Wiener filters (CGWFs). This seems quite important, and it generalizes the previously known result that orthogonal MSWFs are equivalent to CGWFs. Moreover, it suggests that the literature of classical optimization theory may now be mined for efficient algorithms that iteratively add useful dimensions to expanding subspaces for array processing, without the constraint that these new dimensions span an expanding Krylov subspace.

On the negative side, the MSWF and its close cousin the CDWF, require recomputation for each new beamsteering direction in passive sonar. A possible way around this problem is to extend the CDWF to the vector case, wherein the filter is designed to *simultaneously* estimate signals from several different directions. In principle, the number of directions can exceed the number of measurements, making the problem underdetermined. Nonetheless, the CDWF can be applied. One full rank solution will serve simultaneously for many nearby look directions. So there is a need to extend CDWFs for beamforming simultaneously to several directions. Moreover, it remains an open question whether or not there is a true space-time CDWF for estimating the time-series radiated by a source, from an array's worth of

time series data.

As we argue in the section on Modelling and Processing of Nonproper Complex Signals, it is now becoming more clear that complex baseband data cannot be assumed proper, meaning standard linear and Hermitian quadratic forms cannot be considered sufficient statistics, even in the multivariate Gaussian case. Thus there is a need to re-work all of the work on CDWFs for nonproper complex data.

Ref [2] below establishes the role of canonical coordinate and half canonical coordinate mappings in two-channel least squares problems. It derives several *alternating power methods, with deflation*, for computing canonical coordinate mappings. The importance of this work is the following: in spite of the fact that a vector version of the CDWF will construct a useful basis for the matrix Wiener filter, *the system of canonical coordinates is incontestably the optimum coordinate system of a given dimension for partially adaptive filtering.* The problem is computing the system. The results of ref [2] give efficient, time- and order-recursions for tracking canonical coordinates. These results have yet to be applied to beamforming.

2.2 References

1. L. L. Scharf, L. T. McWhorter, E. K. P. Chong, J. S. Goldstein, and M. D. Zoltowski, "Algebraic Equivalence of Conjugate Direction and Multistage Wiener Filters," 12th MIT Lincoln Labs Workshop on Adaptive Sensor and Array Processing, Lexington, MA, Mar 11-13, 2003.

2. A. Pezeshki, L.L. Scharf, M.A. Azimi-Sadjadi, and Y. Hua, "Two-Channel Least Squares Problems: Power Methods for Solving Them and Connections with Canonical Coordinates," IEEE Trans Sign Proc, submitted Apr 1, 2003.

3. L.L. Scharf, J. K. Thomas, and B.D. VanVeen, "Good Canonical Coordinates for Estimation are Bad Canonical Coordinates for Detection, and Vice-Versa," *IEEE Trans Signal Proc,* submitted May 2002, in revision.

   "Kernel-Based Canonical Coordinate

2.3 Open Questions

When extended to the vector case, the CDWF may be used to simultaneously beamform to a multiplicity of beamsteering directions, providing a way to account for correlated multipath. Extended to the time series case, the CDWF may be used to implement full space-time processing of time-series from a multiplicity of array sensors. This is called MIMO processing. So, continuing work in this area would extend the theory of iterative Wiener filtering, wherein expanding subspaces are constructed for signal processing in low-dimensional subspaces, to include

- quasi-Newton algorithms for vector and time-series processing of nonproper complex data, using the CDWF,
- extension of CDWFs to the full MIMO case of estimating and detecting multiple time series, from multiple sources, using a vectors worth of time series at a multisensor array,
- a least squares version of CDWFs that allows recursive time- and order updates of the expanding subspace,
- extension of the CDWF to nonproper complex data, leading to pairwise filtering of complex data, and its complex conjugate,
- time- and order- updates for canonical coordinate maps, applied to partially adaptive beamforming.

3 Beamforming and Diversity Combining in Arrays

3.1 Narrative

In ref [1], communication receivers are derived for two extreme channels: the wavefront fading channel and the element-to-element fading channel. In each case the receiver is a *matched subspace detector*. These results are fundamental to our emerging understanding of sonar array processing in fading channels, for they suggest that a very general array processor should be *trading off local, coherent, linear beamforming against global, noncoherent quadratic diversity combining.* The trick is to determine how much beamforming to

do and how much diversity combining to do. Our current thinking is that a *multiple coherence test* should be run on the multsensor data to determine how to cluster elements into sets that may be beamformed. Then disjoint sets of beamformed elements may be diversity combined. This discussion is reminiscent of subarray processing within large arrays. *What may be original in our discussion is the use of multiple coherence as a clustering test for deciding how to cluster elements into subarrays.* When the channel is fully wavefront coherent, then the clustering test should produce the full array as the single subarray. When the channel is a full diversity channel with no wavefront coherence, then the clustering test should decompose the full array into L subarrays, each consisting of a single element. Of course all interesting cases lie somewhere in between. to be worked out and evaluated, The basic objective of trading beamforming and diversity in large arrays seems to be the correct way to think about the management of spatial and temporal coherence.

In ref [2] below, a new DOA estimator is derived, based on an original ratio of quadratic forms. The estimator outperforms MUSIC at low SNR. generate interest in implementing it on

3.2 References

:

1. M.L. McCloud, L.L. Scharf, and M. Varanasi, "Beamforming, Diversity, and Interference Rejection for Communication over Fading Channels using a Receive Antenna Array," *IEEE Trans Commun,* vol 50, no 1, pp 116-124 , Jan 2003.

2. M.L. McCloud and L.L. Scharf, "A New Subspace Identification Algorithm for High Resolution DOA Estimation," *IEEE Trans Ant and Prop*, vol 50, no 10, pp 1382-1390, Oct 2002.

3. L.L. Scharf, S. Kraut, and L.T. McWhorter, "Capon redux: new formulas, geometries, and computational efficiencies," ASAP 2002, MIT Lincoln Labs, Mar 2002, Mar 12-14; also in preparation for *IEEE Trans Signal Proc.*

3.3 Open Questions

Much of modern passive sonar signal processing is based on the *resolution of a sample covariance matrix.* The quality of this matrix is determined by the number of independent snapshots that may be averaged, leading to the problem of low sample support for nonstationary problems and/or imperfect channels. It seems to us that there is a trade-off between averaging time and length of aperture over which this averaging is done. In a very large aperture, sample support will be limited because spatial coherence will not hold up over a large aperture where angular resolution is fine-grained. It will, however, hold up over short subapertures where resolution is coarse-grained. So the problem of trading detectability and resolution seems to us to be a problem of trading subarray clustering for averaging. A large array that is clustered into subarrays will support more temporal averaging than the large array. Then the subarrays may be used for coherent beamforming with large sample support and the collection of subsarrays may be used for noncoherent diversity combining. Our intuition says the resulting beamformers will consist of matched and adaptive subspace detectors, wherein array data is coherently beamformed within a subarray, and then noncoherently diversity combined across subarrays.

So, continuing work in this area would

- study the problem of trading off temporal averaging and spatial clustering,
- develop and evaluate various coherence tests for clustering of arrays into subarrays,
- develop corresponding matched subspace detectors that combine beamforming and diversity, and analyze performance,
- run beamforming and diversity algorithms on our array simulator to produce bearing responses, bearing-time, and FRAZ plots.

The right way to think about beamforming, whether conventional or modern, is that consecutive snapshots are noncoherently averaged to obtain a sample covariance matrix, which is then tailored with the SVD and used in a beamformer structure like Bartlett, Capon, MUSIC, diagonal averaging, subspace MUSIC, or what have you. If there is temporal coherence to be exploited, then averaging may be done coherently in time, rather than

noncoherently. Continuing work in this area would exploit temporal coherence by coherently averaging before beamforming. This, again, is a topic in beamforming vs diversity.

Another important problem is wavefront compensation for wrinkled wavefronts. One approach, based on the matched subspace detector, is to widen the spatial beamwidth, or subspace bandwidth, by replacing quadratic forms in rank-one beamformers (or steering vectors) with multirank beamformers based on a multidimensional subspace. The subspace is built from a standard steering vector and nearby steering vectors that are constructed from angular derivatives. This allows the wavefront of the propagating field to be any wrinkling of a plane wave that can be modelled as a linear combination of a steering vector and a few of its derivatives. This is a conservative approach that sacrifices spatial resolution for detectability. That is, detectability increases because more energy is accounted for than would be accounted for with a mismatched rank-one beamformer, but resolution is sacrificed because multidimensional subspaces are harder to resolve than one dimensional steering vectors. A more aggressive approach is to try and fit a one-dimensional subspace to the wavefront, by optimizing with respect to a vector of complex phasings that are *designed to iron out the wrinkled wavefront.* Such an approach would aim to take the sample covariance matrix to a low rank matrix by applying a single diagonal demodulation matrix to the snapshots. This is reminiscent of complex demodulation, but here the complex demodulation is not with respect to a single frequency, and it is applied across space, so to speak, and not time. This idea is a variation on a technique called *steered covariance matrices*, but it is designed to iron out wavefronts rather than iron out variations over frequency bands, as originally proposed. It is not yet clear what principle should be used to iron out a wavefront, but one candidate is to design a diagonal phase compensating matrix that minimizes the rank of the sample covariance matrix. Continuing work in this area would use subspace methods to match to wrinkled wavefronts that may be modelled as elements of a multi-dimensional subspace of wavefronts.

4 Matched and Adaptive Subspace Detectors and Estimators

4.1 Narrative

Another area of focus in our research program has been the development of blind adaptive detectors and estimators in interference-dominated problems. In ref [1] below we show that in interference-dominated problems, all principles for detection and estimation in the multivariate Gaussian model produce the same answer, namely an interference rejecting oblique projection, followed by linear or quadratic processing. The structures are naturally low-rank, and they are even more aggressive in their use of singular-value shaping than are the robust adaptive beamformers of Cox and Owsley. We have simulated these detectors on our array simulator. generate interest in implementing them on

The result of ref [2] puts the final touch on what has been a seven-year, ONR-supported, development of matched and adaptive subspace detectors, beginning with the early work of Scharf and his collaborators, and concluding with the work of Kraut and his collaborators. Ref [2] shows that ACE, the adaptive coherence estimator, is uniformly most powerful among all detectors that have the strong false alarm rate property required in adaptive array processing. This is the strongest statement of optimality that can be made for an adaptive detector, and we know of no other detectors for which similar claims can be made.

In ref [3] matched subspace detectors are extended to stochastic signals, for which a preferred direction in a subspace is coded with a probability distribution on the complex mode parameters.

4.2 References

1. L.L. Scharf and M.L. McCloud,"Blind Adaptation of Zero-Forcing Projections and Oblique Pseudo-Inverses for Detection and Estimation when Interference Dominates Noise," *IEEE Trans Signal Proc*, vol 50, no 12, pp 2938-2946, Dec 2002; also L.L. Scharf and M.L. McCloud, "Detection and Estimation when Interference Dominates Noise," Proc 34th Asilomar Conf Signals, System, and Computers, Pacific Grove, CA, Nov 2000; also L.L. Scharf and M.L. McCloud, "Data-Adaptive and Reduced-Rank Detectors and Estimators for Radar, Sonar, and

Data Commmunication," Joint U.S-Australian Conf on Defense Applications of Signal Processing, Adelaide, June 2002.

2. S. Kraut, L.L. Scharf, and R. Butler, "The Adaptive Coherence Estimator is a Maximal Invariant Statistic for Uniformly Most Powerful Invariant Detection," IEEE Trans Signal Processing, to appear 2004; also S. Kraut, L.L. Scharf, and R. Butler, "ACE is Uniformly Most Powerful Invariant," 36th Asilomar Conf on Signals, Systems, and Computers, Pacific Grove, CA, Nov 4-7, 2002.

3. L. T. McWhorter and L. L. Scharf, "Matched Subspace Detectors for Stochastic Signals," 12th MIT Lincoln Labs Workshop on Adaptive Sensor and Array Processing, Lexington, MA, Mar 11-13, 2003; also in preparation for IEEE Trans Signal Procesing.

4. S. Kraut, L. L. Scharf, and L. T. McWhorter, "Adaptive Subspace Detectors," *IEEE Trans Signal Proc*, vol 49, no 1, pp 1-16, Jan 2001.

5. J. Gubner and L.L. Scharf, "Spread Subspace Communications: Power Control, Detectors, and Probability of Error," IEEE Trans Inform Th, to appear 2004; also J. Gubner and L.L. Scharf, "Detection of Subspace Waveforms in Subspace Interference and Noise," Proc ICASSP 2000, Istanbul, June 2000.

4.3 Open Questions

It is almost impossible to come up with anything other than a matched or adaptive subspace detector in multisensor array processing for sonar or radar under the multivariate Gaussian model. We continue to find applications for matched and adaptive subspace detectors, which were discovered under ONR support. Our continuing work has produced *matched direction* detectors, which are an important variation on *matched subspace* detectors. It remains to be seen what role matched subspace and matched direction detectors will play in robust adaptive beamforming with wrinkled wavefronts and/or miscalibrated arrays.

5 Modelling and Processing of Nonproper Complex Signals

5.1 Narrative

All of sonar and radar signal processing is done at baseband, under the assumption that complex baseband signals are proper. Then, typically, only linear and Hermitian quadratic forms are used. But complex baseband versions of real, nonstationary passband signals *are nonproper*, calling into question our basic assumptions and suggesting that *widely linear* and *non-Hermitian* quadratic forms should be used to improve performance of beamformers, detectors, and estimators. In the papers listed below, the theory of nonproper signal processing is extended in several important ways.

Ref [1] below develops the full theory of nonproper complex vectors and processes, including the study of generalized analytic signals. Ref [2] establishes that time-frequency distributions for nonstationary signals (the only ones of interest in sonar and radar) must include the complementary component of the distribution. This has never been done in sonar.

Ref [3] derives a *fundamental limit on the potential processing gain that can be gained with widely linear, as opposed to linear, processing.* This gain is 3 dB for all estimation and detection problems involving complex baseband signals that are nonproper. This is our most important theoretical finding, for it lays the foundation for a host of applications of widely linear processing in sonar and radar. We do not claim that this gain is to be had in all practical applications of the theory, but we do claim that at little additional computing cost, there is potential gain. These results could well be useful for the next refinement to adaptive beamforming. McWhorter has results showing that correlated multipath produces nonproper complex data at baseband, suggesting that widely linear and non-Hermitian quadratic processing might be required to make beamforming and DOA algorithms work in correlated multipath. This would be a revolutionary finding.

5.2 References

1. P.J. Schreier and L.L. Scharf, "Second-Order Analysis of Improper Complex Random Vectors and Processes," *IEEE Trans Signal Proc,* vol 51, no 2, pp 714-725, Mar 2003.

2. P.J. Schreier and L.L. Scharf,"Stochastic Time-Frequency Analysis using the Analytic Signal: Why the Complementary Distribution Matters," *IEEE Trans Signal Proc,* vol 51, no 12 , pp 3071-3079, Dec 2003.

3. P.J. Schreier, L.L. Scharf, and C.T. Mullis, "Detection and Estimation of Improper Complex Random Signals," *IEEE Trans Inform Th,* to appear 2004; also P.J. Schreier and L.L. Scharf, "The Karhunen-Loeve Expansion for Improper Complex Random Signals with Applications to Detection," IEEE ICASSP 2003, Hong Kong, April, 2003; now cancelled, but papers to be published in conference proceedings.

4. P.J. Schreier and L.L. Scharf, "Canonical Coordinates for Reduced-Rank Estimation of Improper Complex Random Vectors," ICASSP 2002, Orlando, FL, May 13-17, 2002.

5. P.J. Schreier and L.L. Scharf, "Low Rank Approximation of Complex Random Vectors," 35th Asilomar Conf Signals, System, and Computers, Pacific Grove, CA, Nov 2001.

5.3 Open Questions

linear and non-Hermitian quadratic There is nothing we can add to this Continuing work in this area would integrate widely linear processing into our work on CDWFs and the clustering of large arrays into smaller subarrays in order to trade beamforming for diversity combining.

6 Time-Varying Spectrum Analysis

6.1 Narrative

In our view, most of sonar array processing is imaginative time-frequency-wavenumber processing from multisensor data, making it a topic in *time-frequency analysis.* In sonar and radar the frequency variable is a vector of frequency and wavenumbers (or equivalently bearing angles). When this time-frequency distribution is averaged over frequency, it is a broadband bearing-time plot, and when averaged over time it is a FRAZ plot. When it is read at a single frequency, it is a narrowband bearing-time plot, and when averaged aver time, it is a narrowband bearing response pattern. When averaged over time and frequency, it is a broadband bearing response pattern.

We have derived a stochastic time-frequency distribution, and kernel methods for estimating it, that is more insightful to us than any others in the literature. Ref [1] below develops the theory of the Rihaczek distribution and proposes a kernel method for estimating it.

6.2 References

:

1. L.L. Scharf, Peter Schreier, and Alfred Hanssen,"The Hilbert Space Geometry of the Stochastic Rihaczek Distribution," *IEEE Trans Signal Proc*, re- submitted June 2004; also L.L. Scharf and B. Friedlander,"Toeplitz and Hankel Kernels for Estimating Time-Varying Spectra of Discrete-Time Random Processes," *IEEE Trans Signal Proc*, vol 49, no 1, pp 179-189, Jan 2001; also L.L. Scharf, B.J. Friedlander, P. Flandrin, and A. Hanssen, "The Hilbert Space Geometry of the Stochastic Rihazek Distribution," 35th Asilomar Conf Signals, System, and Computers, Pacific Grove, CA, Nov 2000.

2. A. Hanssen and L.L. Scharf,"A Theory of Time-Varying Polyspectra," *IEEE Trans Signal Proc,* vol 51, no 5, pp 1243-1252, May 2003; also A.H. Hanssen and L.L. Scharf,"A Theory of Higher-Order Rihaczek Spectra," Proc. IEEE International Conference on Acoust, Speech, Signal Proc, vol 2, pp 1457-1460, Orlando, FL, May 13-17, 2002; also A.H. Hanssen and L.L. Scharf,"Polyspectra for Harmonizable Stochastic Processes," 36th Asilomar Conf on Signals, Systems, and Computers, Pacific Grove, CA, Nov 4-7, 2002; also A. Hanssen and L.L. Scharf, "Polyspectra for Nonstationary Stochastic Processes," NORSIG, 5th Nordic Signal Processing Symposium, Tromso, Norway, Oct 4-6, 2002.

6.3 Open Questions

In our opinion, the literature on time-frequency distributions has been misdirected to deterministic analysis of deterministic waveforms, with a view to characterizing the time-frequency content of a measured pulse. This runs counter to sonar signal processing, where there is less interest in any particular realization of a random process and more interest in the source that could have produced it. For example, two realizations of a random process may

look quite different, but sensible spectrum analysis will reveal that they were produced by the same source, with a characteristic spectrum. The stochastic Rihachek distribution is faithful to the idea of sonar signal processing. Moreover, it extends easily to functions of multidimensional fields, as in the time and space series produced by multisensor arrays. Thus, although ONR remains wary of claims for time-frequency distributions, we continue to think that with sensible adaptation of the stochastic Rihaczek distribution, there may be room for improvement of wideband displays of frequency-wavenumber (or bearing) distributions that vary with time. Moreover, it now seems clear that there is a direct connection between the problem of nonstationary spectrum analysis and the identification of channel scattering fundtions in active sonar. So, continuing work in this area would involve

- extension of the Rihaczek spectrum to vector functions of multidimensional space-time fields,
- development of kernel estimators of the the Rihaczek spectrum,
- development of a theory of Rihaczek distributions for estimating sonar scattering functions.

7 Array Simulator

7.1 Narrative

We have programmed in MATLAB an extensive multisensor array simulator. This simulator models channels with fairly arbitrary spatial and temporal coherence of the propagating fields. Thus a full range of beamforming algorithms can be tested against simulated array data. The resulting beamformer outputs are displayed as bearing responses or as bearing time plots. We have programmed all standard beamformers, and most modern reduced-rank beamformers that SVD sample covariance matrices and shape singular values.

7.2 References

1. R. Sipes, "An Array Simulator for Beamforming," Colorado State University Report, Dec 2002.

7.3 Open Questions

Continued development of our array simulator would involve by programming the following features into the software:

- discrete multipath so that the effects of correlated multipath can be modelled,
- coherence testing so that algorithms for clustering large arrays into subsarrays can be tested,
- MIMO versions of the CDWF so that true space-time versions of subspace expanding filters can be implemented.

8 Students Graduated

Shawn Kraut, Assistant Professor of Mathematics and Electrical Engineering, Queen's University

Mike McCloud, Assistant Professor of Electrical and Computer Engineering, University of Pittsburgh

9 Awards

Shawn Kraut, IEEE Signal Processing Best Paper Award for an Author under Thirty Years of Age, for S. Kraut, L.L. Scharf, and L.T. McWhorter, "Adaptive Subspace Detectors," IEEE Trans Signal Processing, vol 49, No 1, pp 1-16, Jan 2001, written under ONR support.